TAXONOMY AND HERBARIA IN SERVICE OF PLANT CONSERVATION: LESSONS FROM MADAGASCAR'S ENDEMIC FAMILIES[1]

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Abstract

Our actions during the next two decades will largely determine how many of the world's ca. 300,000 species of vascular plants will survive for future generations. The fundamental data that define both the taxonomic frameworks within which species are circumscribed and delimited from related species, as well as the geographical distributions of those species, reside in the world's ca. 3000 herbaria. These herbaria, and the taxonomists who work in them, can and must play a critical role in identifying as rapidly as possible those species most threatened with extinction. A project that has focused on the species in Madagascar's seven endemic plant families has demonstrated the necessity of reviewing, and then revising when necessary, the existing taxonomic framework. Comprehensive databasing and georeferencing of primary occurrence data then facilitated simple GIS analyses of Extent of Occurrence, Area of Occupancy, estimates of the number of "subpopulations," and their presence/absence in protected areas, all of which are parameters that contribute to an expedient preliminary assessment of extinction risk. In addition, simultaneous mapping of all species in the endemic families revealed centers of species richness and endemism of particular conservation importance: both those already incorporated in the protected areas system, and, more importantly, those that currently fall outside of the protection network. Partnerships among the world's herbaria can efficiently achieve an initial global assessment of the most threatened vascular plant species by focussing on taxa endemic at political and regional (e.g., Hotspot) scales. The synthesis and analysis of the primary data housed in the world's herbaria—our only incontestable record of plant life on Earth—constitutes the most effective and robust means of directly informing conservation planning, and thereby minimizing the loss of plant diversity.

Key words: conservation, natural history collections, primary occurrence data, taxonomy.

As the term "biodiversity" has entered the international lexicon of the environment during the past decade, one of the most fundamental aspects of the concept has often been neglected: principal knowledge of biological diversity emanates from the study of natural history collections by taxonomists. Plant taxonomists utilize herbarium specimens to erect taxonomic frameworks within which species are defined, circumscribed, and delimited from related species. In addition to portraying the limits of variability of individual taxa, those herbarium specimens representative of a given taxon also constitute primary occurrence data that collectively depict the verifiable (i.e., vouchered) geographical distribution of the taxon. Thus, herbaria, and the taxonomists who examine, classify, and curate the primary specimen data that reside in herbaria, furnish the "what," "where," and "when," initially necessary to document plant life on Earth. As such, they have a unique and critical role to play in global efforts to mitigate the loss of biodiversity. Recent studies of the families of vascular plants endemic to Madagascar (Schatz et al., 2000a) demonstrate that central to such a role is the revisiting, reattributing, and synthesis of the primary data itself.

Tens of thousands of plant species have already been listed as threatened with extinction. The *1997 IUCN Red List of Threatened Plants* (Walter & Gillet, 1998), *The World List of Threatened Trees* (Oldfield et al., 1998), and their to-be-revised-yearly electronic Internet successor, *2000 IUCN Red List of Threatened Species* (see [IUCN]), serve as sober-

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Table 1. Malagasy endemic plant families: Revised (since 1998) taxonomic frameworks.

	No. of species	Newly recognized	Newly described	Placed into synonymy
Asteropeiaceae	8	3 (38%)	2 (25%)	—
Didymelaceae	2	—	—	—
Kaliphoraceae	1	—	—	—
Melanophyllaceae	6	1 (17%)	1 (17%)	4
Physenaceae	2	—	—	—
Sarcolaenaceae	60	25 (42%)	23 (38%)	—
Sphaerosepalaceae	18	2 (11%)	—	—
Total (%)	97	31 (32%)	26 (27%)	4

ing baselines on the state of the Earth's plant resources. As commendable as these efforts are, the fact remains that the majority of plant species have not yet been evaluated with regard to their risk of extinction. As would be expected, the lists are heavily biased in their representation to the comparatively well-known floras of Europe and North America, and to a lesser degree Australia and South Africa, or to specific taxonomic groups (e.g., conifers, palms) or life forms (e.g., succulents) popular in cultivation. One suspects therefore that the number of threatened plant species identified thus far is only the tip of the iceberg. In the absence of an exhaustive survey of all ca. 300,000 (or more?) species of vascular plants (Prance et al., 2000), a strategy to identify and safeguard those remaining species most at risk of extinction must be implemented as rapidly as possible. How can the daily work of herbaria and taxonomists contribute to such a strategy and thereby directly inform conservation planning?

Conservation Assessments Based on Old Taxonomy Will Be Inadequate and Misleading, Because They Fail to Include Recent Primary Data: Revisiting the "What"

The goal of the Endemic Families of Madagascar Project has been to provide current assessments of the conservation status of all species in the seven families of vascular plants endemic to Madagascar and the Comoro Islands (Schatz et al., 2000a). An essential first step in that process was the reevaluation of existing taxonomic frameworks for each of the families, four of which were originally subsumed within non-endemic families: Asteropeiaceae within Theaceae (Perrier de la Bâthie, 1951); Kaliphoraceae and Melanophyllaceae within Cornaceae (Keraudren, 1958); and Physenaceae within Capparaceae or Flacourtiaceae (Perrier de la Bâthie, 1946). The available taxonomy prior to our review dated on average to 1952 (ranging from 1937 to 1963). Reevaluation of existing taxonomic frameworks entailed examination of all primary specimen data. In the case of three of the families—Didymelaceae (Leandri, 1937), Kaliphoraceae, and Physenaceae—together comprising just five species, the most recent frameworks remain valid. But in the remaining four families—Asteropeiaceae, Melanophyllaceae, Sarcolaenaceae (Cavaco, 1952), and Sphaerosepalaceae (Capuron, 1963)—review of all primary data necessitated their taxonomic revision (Randrianasolo & Miller, 1999; Schatz et al., 1998, 1999a, b, 2000b, 2001; Lowry et al., 1999, 2000). In all but one instance, a synoptic format for the revisions was adopted for the sake of expediency: the revised taxonomic framework was illuminated through new identification keys emphasizing diagnostic features, and full synonymy for each taxon was given, but only the newly described species were provided with full descriptions. These revised taxonomic frameworks include 31 newly recognized species (or 34% of the 92 total species now enumerated in those four families), 26 of which were newly described; 4 formerly recognized species and a number of infraspecies were placed into synonymy (Table 1). Primary data that had been collected since publication of the former frameworks accounted for 19 (73%) of the 26 newly described species. In the remaining 12 newly described or recognized species, specimens ascribed to other species in the previous taxonomy were judged to represent clearly discernible, distinct taxa based upon morphological and ecogeographic criteria. Conversely, in the cases of species and infraspecies now placed into synonymy, formerly cited specimens, in conjunction with newly available material, revealed taxa that could no longer be distinguished from earlier described species. Clearly, assessments of conservation status based on the taxonomies that existed prior to our reevaluation would have been highly flawed and misleading, and would have failed entirely to account for one third of the species now recognized in the seven endemic families.

Conservation is All about Geography, but Most of Plant Diversity is Not Geo-referenced: Reattributing the "Where"

Mapping the primary occurrence data upon which a taxonomic framework stands has long been a preoccupation of taxonomists: most revisions include distribution maps of the taxa. Distribution mapping is usually a tedious task insofar as the majority of primary data collected prior to the latter decades of the 20th century are only imprecisely located in relation to population centers or physiographic features of the landscape, but lack the precise geographical coordinates that can now be assigned so easily in the field with Global Positioning System (GPS) technology. As a consequence, most of plant diversity must be *post facto* geo-referenced in order to capitalize on the current revolution in computer mapping and spatial analysis brought about through Geographical Information Systems (GIS) tools. Geo-referencing of primary data representing the Malagasy endemic families has been greatly facilitated by the compilation of a *Gazetteer to Malagasy Botanical Collecting Localities* [Schatz & Lescot, 2001]. Some historical specimens that lack coordinates may simply be impossible to geo-reference to a scale that has meaning for conservation. In the majority of cases, however, geo-referencing can be achieved to obtain a Minimum Mapping Unit of plus or minus one minute of latitude/longitude, more than sufficient for the coarse area estimates used in conservation assessments. Even in cases of uncertainty involving collections known to originate from within protected areas in Madagascar, but without any greater precision, e.g., the *Réserves Naturelles* or *RN* collection series, mapping to the centroid of the protected area polygon still constitutes a valuable reattribution that can be included in area and subpopulation estimates. Of even greater importance is that collections in the *RN* series document historical presence within the protected areas network.

With new and reconfirmed taxonomic frameworks in place that are based on the totality of available primary data, the next step in assessing the conservation status of each species entails analysis of its geography, including the geography of current land cover and threat. Conservation ultimately depends on sufficient space to maintain a viable population, the size of which will vary considerably from one species to another depending upon life histories and habitat requirements. Although ideally one would want to conduct a long-term Population Viability Analysis (PVA) to determine exactly what constitutes "sufficient space" for each species, area measurements calculated directly with GIS tools based solely on the primary occurrence data can provide a rapid first estimate of a species' vulnerability to threat, and therefore a means of prioritizing concern. Among the assumptions inherent in such an initial evaluation are: (1) that the known collections and localities for a given species are a valid reflection of its abundance and distribution; (2) that widespread and common species will be at lower risk than restricted and rare species; and (3) that species occurring within protected areas will be at lower risk than species that occur only outside of protected areas. The *IUCN Red List Categories* (IUCN, 1994; IUCN/SSC Criteria Review Working Group, 1999) serve as a guideline for incorporating the area measurements of Extent of Occurrence and Area of Occupancy into a hierarchical delineation of extinction risk. For example, among the species in the endemic Malagasy families, newly described *Melanophylla modestei* G. E Schatz, Lowry & A.-E. Wolf (Melanophyllaceae) (Schatz et al., 1998), is classified as Critically Endangered (CR) given an Extent of Occurrence less than 100 km², an Area of Occupancy less than 10 km², and a single known population (Schatz et al., 2000a). On the other hand, *Asteropeia densiflora* Baker is classified as Vulnerable (VU) due to an Extent of Occurrence less than 20,000 km² (Fig. 1), an Area of Occupancy less than 2000 km² (Fig. 2), and less than 10 known "subpopulations" (the number of non-contiguous occupied cells or cell clusters within the 10 km × 10 km grid utilized to estimate the Area of Occupancy) (Fig. 2) (Schatz et al., 2000a).

In addition to facilitating rapid area measurements that can be incorporated into evaluations of extinction risk, reattributing primary data with geographical coordinates also allows the modeling of potential distribution (Skov, 2000; see also [BIODI] and [Species Analyst]). Utilizing the spatial analytical functions of GIS, an envelope of independent physical and environmental variables associated with a set of primary occurrence data points can be described, and in so doing define an environmental niche, and hence, a potential distribution that corresponds to the range of documented heterogeneity. When compared against current land cover as revealed from satellite imagery, remaining viable habitat coinciding with (preferably recently) documented distribution can be identified. In the absence of extant viable habitat that intersects the documented distribution, i.e., when all historical

Figure 1. Extent of Occurrence (= 17,830 km^2) of *Asteropeia densiflora* Baker in Madagascar.

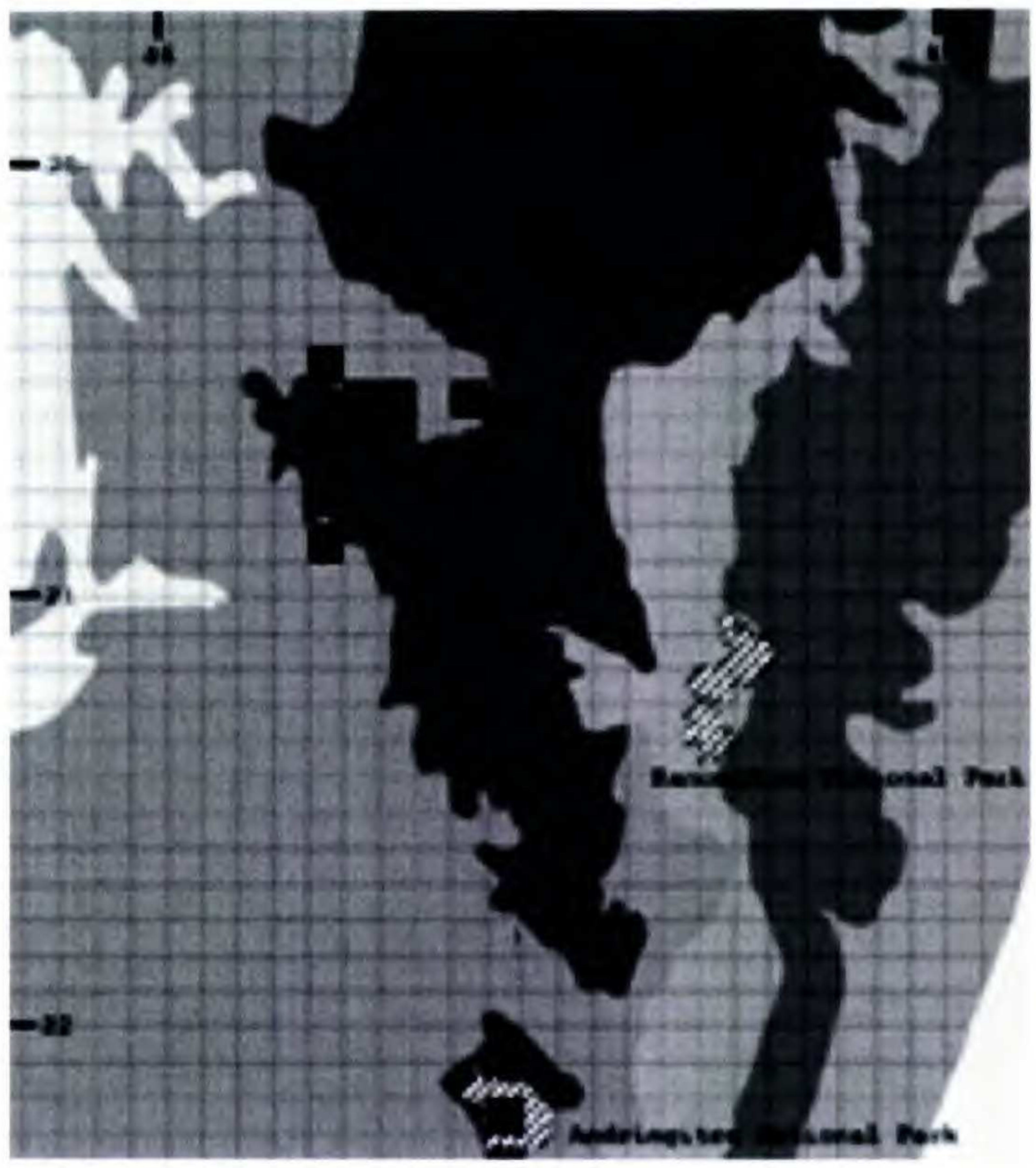

Figure 2. Area of Occupancy (= 1800 km^2) and number of "subpopulations" (7 individual cells + 2 cell clusters = 9) of *Asteropeia densiflora* Baker in Madagascar as defined by a 10 km × 10 km grid.

primary data originate from areas now converted to urban or agricultural uses, conservation hopes for a species may still lie within areas of potential distribution and remaining viable habitat.

Conservation in such places as Madagascar may ultimately depend upon encompassing a species within some type of protected area. An overlay of protected areas polygons in relation to primary occurrence data instantly reveals if a "gap" in protection exists. Among the 97 species in the seven families endemic to Madagascar, at least 28 species are not presently recorded from protected areas. The situation is potentially far bleaker for the species endemic to Ecuador, where over 75% of the 4011 endemic species are not yet documented in protected areas (Valencia et al., 2000). Similarly, the 1995 revised ROTAP (*Rare or Threatened Australian Plants*) listing (Briggs & Leigh, 1996) reveals that 47% of the 5031 listed taxa are not documented from protected areas. If one goal of conservation is to ensure that the maximum number of species is included within the protected areas network, then considerations of complementarity dictate that centers of endemism, i.e., concentrations of co-occurring local endemic species, be identified (Williams, 1999). For Madagascar, simultaneous mapping of all species in the endemic families revealed, for example, that the Ibity/Itremo Massifs on the Central High Plateau, which are geologically characterized by a complex mosaic of granitic, marble, and quartzite substrates, constitute an important center of endemism that is *not* currently encompassed within the protected areas network. Of the ten endemic families' species recorded from Ibity/Itremo, five (all Sarcolaenaceae)—*Leptolaena diospyroidea* (Baill.) Cavaco, *Pentachlaena latifolia* H. Perrier, *Perrierodendron quartzitorum* J.-F. Leroy, Lowry, Haevermans, Labat & G. E. Schatz, *Schizolaena microphylla* H. Perrier, and an undescribed species of *Xerochlamys/Sarcolaena*—are essentially restricted to the Massifs, and are therefore entirely lacking protection. The presence of numerous other local endemics in the Ibity/Itremo Massifs, including a number of legumes (Du Puy & Moat, 1998), forcefully argues for the immediate establishment of new protected areas in the region. Simultaneous mapping of all species in the endemic families also revealed the importance and management needs of existing protected areas. In particular, the small Réserve Naturelle Integrale of Betampona (2228 ha) shelters 20 species in the endemic families, including two newly described as a result of revised taxonomies within Sarcolaenaceae (*Pentachlaena betamponensis* Lowry, Haevermans, Labat & G. E. Schatz and *Rhodolaena leroyana* G. E. Schatz, Lowry & A.-E. Wolf) that are known only from this reserve. Mapping reattributed primary occurrence data of restricted range species, i.e., country endemics, or species endemic to Ecoregions (Olson & Dinnerstein, 2002 [this volume]) or Hotspots (Myers et al., 2000), may well constitute the most efficient and robust means of directly informing conservation planning.

MUCH OF PLANT DIVERSITY IS "RARE," I.E., DOCUMENTED BY VERY FEW COLLECTIONS, AND HERBARIA AND THEIR ASSOCIATED DATA ARE IDIOSYNCRATIC: STRATEGIES AND NEW STRUCTURES FOR RAPIDLY ACHIEVING THE SYNTHESIS OF REATTRIBUTED PRIMARY DATA

Faced with the very real prospect of losing a significant proportion of the estimated 300,000 or more species of vascular plants during the coming decades, it is incumbent upon the systematics community to synthesize the most relevant primary data, and disseminate that data to governments and the conservation community. By definition, such a synthesis must go beyond Red Lists per se as they are currently envisioned by IUCN (see [IUCN]). Although Red Lists attempt to draw attention to the species most at risk of extinction, because they lack the underlying geo-referenced primary data, they have only very limited utility for conservation planning. Nevertheless, Red Lists in their current form, along with country and regional checklists, can help guide the prioritization of primary data synthesis. By identifying the greater than 25% of Ecuadoran species known only from the type collection, and the greater than 50% known from only one or two populations, and conversely, the less than 10% that are "common" (known from ten or more populations), the *Ecuador Red List of Endemic Plants* (Valencia et al., 2000) serves to prioritize which species should be subject to comprehensive primary data synthesis. Similarly, ROTAP lists nearly 200 Australian species known only from the type collection (Briggs & Leigh, 1996). Surely, a comprehensive synthesis of all vascular plant species known only from their type collection, and the geo-referencing of as many as possible, must be one of the very first priorities.

Species known only from a single (type) collection are merely an extreme case of endemism. Within the context of the Convention on Biological Diversity (see [CBD]), governments are obligated to pay particular attention to all those species endemic within their borders. Among the nearly 34,000 species listed in the *1997 IUCN Red List of Threatened Plants* (Walter & Gillet, 1998), 91% were single-country endemics. The recent *Red Book of Iran* (Jalili & Jamzad, 1999) evaluates all 1727 endemic species (22% of the total flora), and the Ecuador *Red Book* focuses solely on the endemic species. What is required next is the assimilation and geo-referencing of the primary data of all of these, as well as every other country's endemic taxa. Priority should be accorded to species representative of endemic higher taxa, i.e., families and genera. A similar approach should be adopted within the framework of the new Critical Ecosystem Partnership Fund initiative (see [CEPF]), which seeks to address conservation needs at a regional scale, as delimited by conservation Hotspots, which are themselves defined in part by a minimum number (1500) of endemic plant species (Myers et al., 2000). Knowing where the endemic species occur (or at least occurred at some point in the past, and might possibly still occur) within countries or regions is fundamental for the rational allocation of finite conservation resources.

But as the review of all primary data representing the Malagasy endemic families has demonstrated, knowing where the endemic species occur must be predicated on knowing just what the endemic species are. Catalogues such as those for Ecuador (Jørgensen & León-Yánez, 1999) and Peru (Brako & Zarucchi, 1993) involve some review of the primary data, but generally do not exhaustively inventory all existing specimens. Revised taxonomic frameworks, however, should in theory be based upon examination of all existing collections, and therefore represent the most appropriate and opportune point at which to disseminate reattributed primary data. Indeed, deposition of reattributed primary data into an Internet-accessible database should be a sine qua non for publication of a revised taxonomic framework, just as deposition of nucleotide sequence data into GenBank (see [NCBI]) has become (in most cases) a necessary precondition for publishing phylogenetic frameworks. For revised taxonomies of the Malagasy endemic families, comprehensive, reattributed (i.e., geo-referenced) primary data have been deposited in the world's largest botanical specimen database, to which Internet access is provided through W³TROPICOS (see [MBG]). Recent discussion of the state of bioinformatics for biodiversity has sounded the call for improved infrastructure, and highlighted various developments involving remote query and retrieval from multiple, so-called distributed databases (= "interoperability") (Bisby, 2000; Edwards et al., 2000; Krishtalka & Humphrey, 2000). Nevertheless, in conjunction specifically with the publication of revised taxonomic frameworks, it would seem appropriate and extremely

Table 2. Representativeness of TROPICOS specimen database on 10 October 2000.

- 1.5 + million specimen records
- 922,668 geo-referenced
- 1.14 million identified to spp. representing 117,806 spp.
- 45,752 spp. (39%) represented by only 1 specimen
- 62,709 spp. (53%) represented by 1 or 2 specimens
- 96,456 spp. (82%) represented by 10 or less specimens
- 4,742 spp. (4%) represented by 50 or more specimens

useful to establish a GenBank analog ("SpecimenBank") for deposition of the underlying geo-referenced primary data. The utility of recent *Species Plantarum—Flora of the World* (see [ABRS]) treatments of Irvingiaceae (Harris, 1999), Stangeriaceae (Steyn et al., 1999), and Welwitschiaceae (Steyn & Smith, 1999) would be significantly enhanced if the underlying primary data were accessible from an Internet specimen database. Just as the nucleotide sequences in GenBank document the microgeography of biodiversity, natural history collections define its macrogeography. Obvious linkages between the two scales should be made, as well as to seedbanks and living germplasm collections (at [IPGRI] and [NPGS]).

Although the TROPICOS database of the Missouri Botanical Garden does contain some exhaustive sets of primary data such as those assimilated in the course of the review and revision of the Malagasy endemic families, in general, it reflects the idiosyncratic, incomplete nature of herbaria and their associated specimen data. The sources of the representativeness of TROPICOS (mostly contemporary collections from a limited number of regions), wherein 117,806 species are represented by 1.5+ million specimens, dictate that the majority of species are represented by only one or two specimens; conversely, only 4% are represented by 50 or more specimens (Table 2). Just as taxonomic revisions require the pooling of primary data from numerous herbaria, the synthesis of such data for conservation must also involve "North/South" herbarium databasing partnerships. For any given country or region of the world, usually a limited number of internal and external herbaria hold the majority of unique primary data. Adopting a species by species approach, and beginning with those endemic to countries and regions, North/South herbarium partnerships should work to synthesize primary data into a global plant conservation database. A model already exists to emulate for the development of such a database. Botanical Garden Conservation International (see [BGCI]) serves as a coordinating body to galvanize ex situ plant conservation efforts at over 500 member botanical gardens, maintaining a database of the ca. 85,000 species currently in cultivation in those gardens. Similarly, the 3000 herbaria worldwide (Holmgren et al., 1990), and indeed, the ca. 215,000+ plant species *not* yet in cultivation, would benefit tremendously from an analogous coordinating body ("Herbarium Conservation International") to help facilitate databasing partnerships for the synthesis of primary data that could directly inform in situ plant conservation. Such a coordinating body would assist in the organization of regional herbarium networks such as the highly successful Southern African Botanical Diversity Network (see [SABONET]), and ensure that they are partnered with the appropriate Northern herbaria. The ongoing Red List Program within SABONET (Golding, 1999a, 1999b, 2000) would be greatly enhanced from formalized partnerships with the Northern herbaria where the majority of primary data from the region are housed.

The task of synthesizing primary data of the most threatened plant species is large, but by no means insurmountable. The analysis of over 4000 Ecuadoran endemic species was achieved within a little over a year of the publication of the Ecuador *Catalogue.* With ca. 300,000 species to track, and 3000 herbaria, each herbarium would need to take responsibility for only 100 species on average. *Index Herbariorum* lists 8800 staff working at the 3000 herbaria; throw in an additional 1200 students and volunteers, and each person would be responsible for collating the primary data of just 30 species on average. In fact, the task is not even that great. There are numerous widespread species of little or no conservation concern (except when their invasive capacity leads to the displacement of indigenous species). The problem should thus be attacked from both ends, identifying both the most widespread and "weedy" species, as well as those represented only by one or several collections. Momentum is building to synthesize information on invasive species globally (see [GISP] and [NBII]), but there is as yet no organized effort to tackle the latter, i.e., the rarest of species. Similarly, great progress (sometimes even with redundant and overlapping efforts) is being made to diffuse the "names" of biodiversity (see [ABI], [IPNI], [IOPI], [ITIS], [Species 2000]). However, as governments and conservation organizations seek to prioritize and protect remaining tracts of viable habitat, it is imperative that they have access to more than just the "what" of threatened biodiversity. "Names" have meaning only in relation to the primary data that define them: originally by their types, and then subsequently all the other specimens assigned to them by taxonomists in the course of trying to order the grand diversity of life. Therefore, by definition, the meanings of plant "names" cannot remain static. Each new collection expands the meaning in space and/or time, and has the potential to significantly modify or alter the meaning, or even to define a new name. To maximize the number of plant species that will survive the current extinction wave, we must also furnish the "where" of rare and threatened plant species, continually revisiting and reattributing the primary specimen data, our only incontestable record of life on Earth.

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